Searching for Fast Optical Transients using a VERITAS Cherenkov Telescope

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ABSTRACT

Astronomical transients are intrinsically interesting things to study (eg: gamma ray bursts, supernovae, solar flares). Fast optical transients (microsecond timescale) are a largely unexplored field of optical astronomy mainly due to the fact that fast transient events are speculative and large optical telescopes are oversubscribed. Also, most optical observations use instruments with integration times on the order of seconds and are thus unable to resolve fast transients. The current generation of atmospheric Cherenkov gamma-ray telescopes, however, have huge collecting areas (eg, VERITAS, which consists of four 12-m telescopes), larger than any existing optical telescopes. Their optics are less precise but as "light buckets" they are unsurpassed. Time is typically available for such studies without interfering with gamma-ray observations. The following outlines the benefits of using a Cherenkov telescope to detect optical transients and the implementation of a dedicated photometer based on field programmable gate arrays.

Introduction

Searching for events with sub-second timescales is largely unexplored field of optical astronomy. Most optical observations are made with instruments (e.g. CCDs) with fairly long integration times; on the scale of seconds to minutes (or more) so any fluctuations happening on a shorter timescale than this go unseen. Given that time on large optical telescopes is difficult to attain, and that ultra-fast optical transients (μs- timescale) are speculative, few attempts have been made to search for them.

The ability to gather as many photons as possible is more desirable than the ability to resolve the target object when searching for ultra-fast optical transients. Thus, atmospheric Cherenkov detectors, while lacking in angular resolution, perform very well as "light buckets" and typically have much larger effective collection areas:

Optical Telescopes		Cherenkov Telescopes		
	Diameter (m)		Diameter (m)	# of Telescopes
GTC	10.4	VERITAS	12	4
LBT	11.7	H.E.S.S.	12	4
KECK	10	MAGIC	17	2
SALT	9.2	CANGAROO	10	4

Making optical observations with Cherenkov telescopes is not new, as most Cherenkov experiments have made measurements of the Crab optical pulsar. The first searches for optical transients, however, were made by H.E.S.S. in 2009[1], and are the inspiration for this experiment. In 43 hours of observing, H.E.S.S. only detected eight events with durations $3\mu s < \tau < 500\mu s$ wherein the background is expected to be low. Five were determined to be lightning and the other three a piece of space debris. It is believed that greater sensitivity and more observation time is required to detect ultra-fast transients.

Observations can be made under moonlight when Cherenkov telescopes are not taking gamma-ray data and time is readily available. The following sections outline possible ultra-fast optical transient sources and the design of a dedicated ultra-fast photometer based on field programmable gate arrays (FPGA).

Possible Source Types

The emission mechanism for ultra-fast optical transients is likely the accretion of matter onto high-mass compact objects (*i.e.* high-mass X-ray binaries). To date, no astronomical sources of optical transients on timescales less than 100μs have been found, but compact objects are known to produce bright, short optical flares. Millisecond optical transients have been observed for X-ray binaries[2] and pulsars[3], and searched for in rotating radio transients (RRATs)[4], which exhibit transient radio events on the scale of a few ms. The duration of the flares and their brightness offer insight into their emission mechanisms: they are likely sources of synchrotron radiation[5] rather than thermal sources.

Within the past few years, it has been shown that nonthermal ultra-fast optical transients are at least theoretically possible. Ultrarelativistic "fireballs" with high enough Lorentz factors could produce optical transients with timescales of 10^{-5} to 10^{-4} seconds alongside gamma-ray bursts[6] (albeit they may be extremely faint).

Feasibility

Following [1], consider an optical telescope with diameter D_O and a flare of duration τ. Assuming that the optical telescope is free of background noise, the minimum detectable flux ϕ_O is set by requiring that the telecope collect at least one photon:

$$\phi_O \sim \frac{4}{\pi}\frac{1}{D_O^2\tau}.$$

A Cherenkov telescope will be limited by the shot noise from the night sky background (NSB) which is assumed to be isotropic with flux ϕ_{NSB} and a background of

$$B = \phi_{\mathrm{NSB}}\left(\frac{\pi}{4}\right)^2 D_C^2\sigma_C^2\tau,$$

where D_C^2 is the diameter of the Cherenkov telescope and σ_C is the field of view of a single photodetector. The noise N is the Poisson noise $N = \sqrt{B}$.
For any signal to be discerned, the signal must be at least as large as the noise. Also, the signal must be equal to or larger than the minimum detectable flux and proportional to both the flare duration and collecting area of the telescope:

$$S = \phi_C\frac{\pi}{4}D_C^2\tau,$$

Thus, ratio $S/N = 1$ yeilds a minimum detectable flux ϕ_C for a Cherenkov telescope to be

$$\phi_C = \frac{\sigma_C}{D_C}\sqrt{\frac{\phi_{\mathrm{NSB}}}{\tau}}.$$

Comparing the minimum detectable fluxes for the optical and Cherenkov telescopes yeilds an interesting result:

$$\frac{\phi_C}{\phi_O} = \frac{\pi}{4}\frac{\sigma_C}{D_C}D_O^2\sqrt{\phi_{\mathrm{NSB}}}\sqrt{\tau},$$

i.e. for short enough flares, the minimum detectable flux of a Cherenkov telescope can be equal to or lower than that of an optical telescope. Fig.1 depicts the equivalent optical telescope diameter for a flare duration τ at various values of ϕ_{NSB} for $\phi_C = \phi_O$.

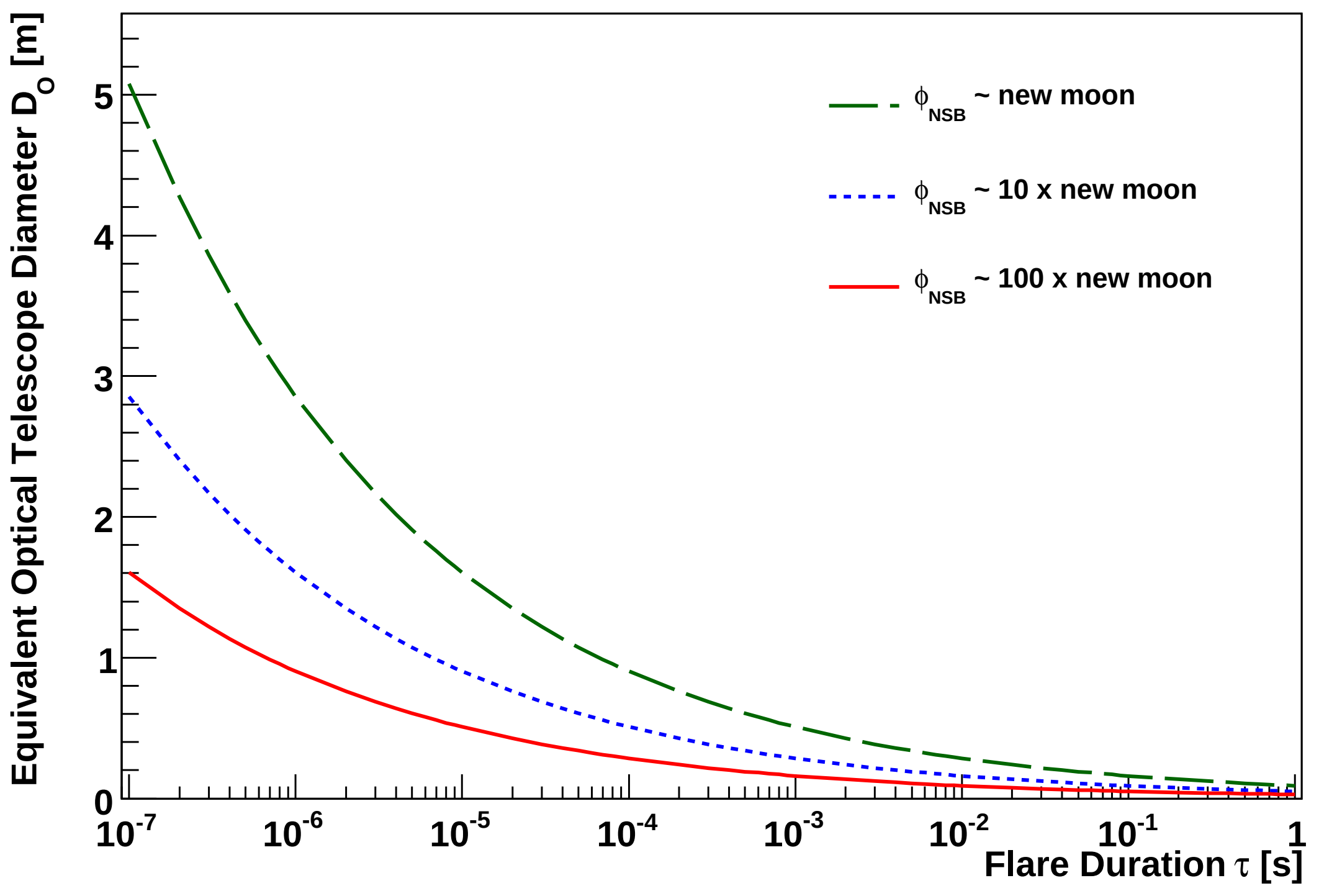

Figure 1: For the condition $\phi_C/\phi_O = 1$, the equivalent optical telescope diameter is plotted against flare duration for a VERITAS telescope (D_C = 12m, $\sigma_C = .06°$ (the typical VERITAS PSF size), $\phi_{NSB} = 3.2 \times 10^{12}$ photons/ s sr m^{-2}).

The Photometer

The Camera

The VERITAS camera is composed of 499 close-packed pixels (Fig.2). By taking the central seven pixels of the camera, one has a centre pixel surrounded by a ring of six others. The ring provides a measure of the background and it provides the ability to veto non-astronomical sources of transient events. Each of the pixels on the VERITAS camera is a photomultiplier tube contained within a hexagonal light cone with a field of view of about 0.15°. Given that the optical PSF of the telescope is 0.06°, when it is pointed at a star (*i.e.* a point source), all the light will be contained within the central pixel. Non astronomical sources, such as meteor showers and aircraft, will either have a signature that is not contained within a single pixel, or will be localized to one pixel but move across the camera over time (see Fig.3). Hence, any events not fully contained within the central pixel can be immediately rejected in the offline analysis.

The Data Acquisition System (DAQ)

Each of the photomultiplier tubes of the camera will be connected to a signal discriminator. The discriminated signal will then be passed to a level translator to convert the negative voltage signal to a positive voltage signal such that the main component of the DAQ, an FPGA, can count the number of incoming signals. Fig.4 is a block diagram depicting the process flow for the detector.

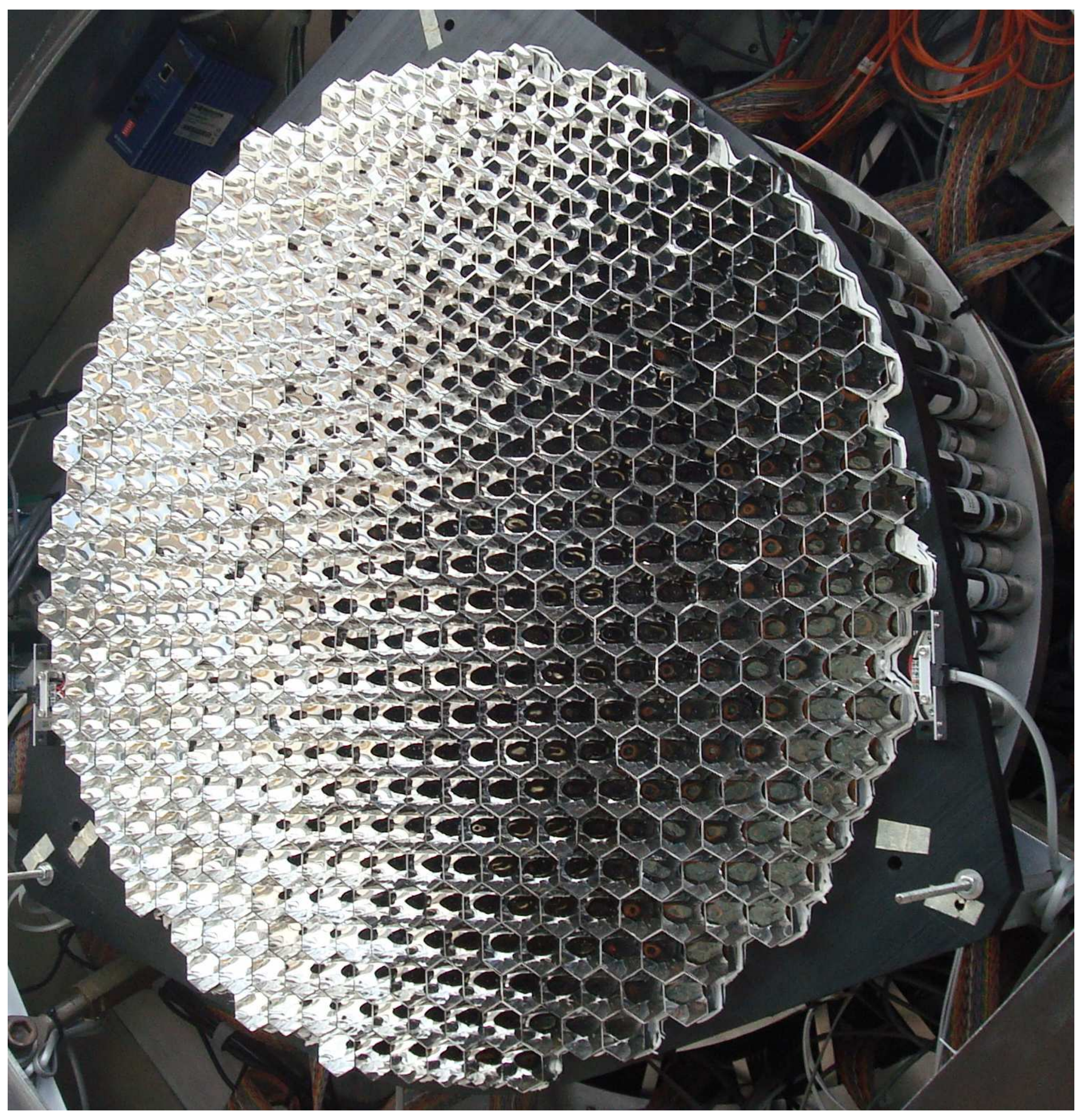

Figure 2: The VERITAS camera is made up of 499 photomultiplier tubes with attatched light cones to minimize dead space. The photometer will use only the centre seven pixels.

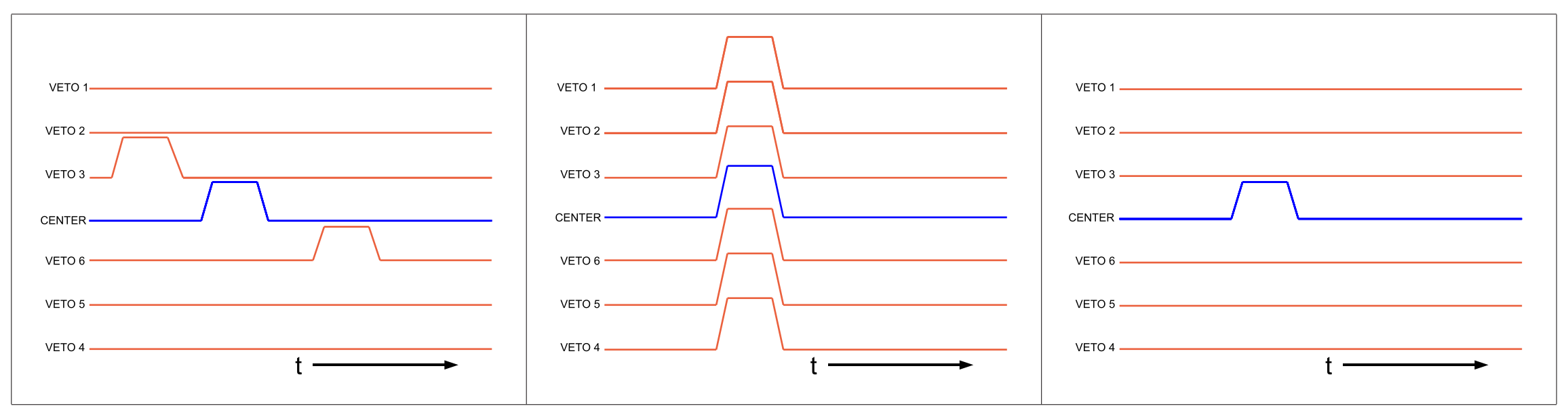

Figure 3: Three possible events. The veto ring is indicated in red, the centre pixel in blue. Left: An object passes through the field of view of the camera, causing a signal in a veto pixel, the centre pixel and the opposite veto pixel. Centre: A lightning flash illuminates all pixels simultaneously. Right: A "good event" where the only measured signal is in the central pixel.

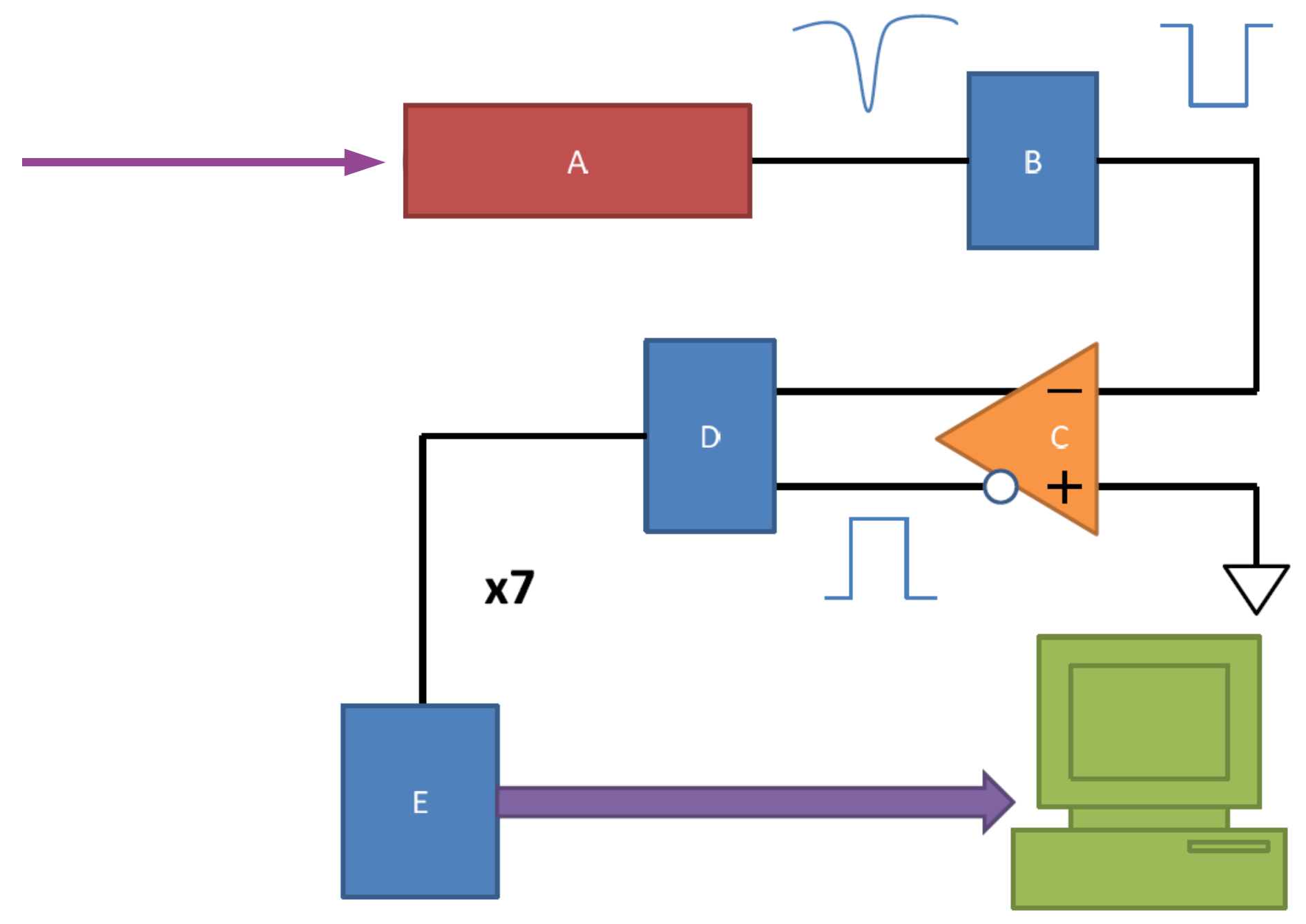

Figure 4: A photon enters a PMT (A). The signal is discriminated (B) and then fed into a high speed LVDS (low voltage differential signaling) comparator (C) which produces positive voltage logic with signal response times on the order of 1ns. The signal is fed into a scaler (D) which counts the signal. A microprosessor embedded in the FPGA (E) reads in the scaler values as fast as possible (currently 17μs) and stores them to a memory buffer which is subsequently read out over Gigabit Ethernet to a waiting computer. Flares are then searched for in the offline analysis by computing the rates. In principle, were a flare observed, the rate would increase for a period of time before settling back to its mean value (as seen in Fig.3).

Conclusion

The design for a μs timescale optical transient detector using a seven pixel camera and an FPGA has been outlined. Optical transients at timescales of tens to hundreds of microseconds from galactic microbursts or baryon-free GRBs are theoretically possible. Currently, the photomoter is nearing completion and is slated for use in the near future.

Acknowledgements

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